



UNIVERSITI MALAYA

INAUGURAL LECTURE

**Direct Brain-Computer
Communication
and its Application
for Neuroprosthesis**

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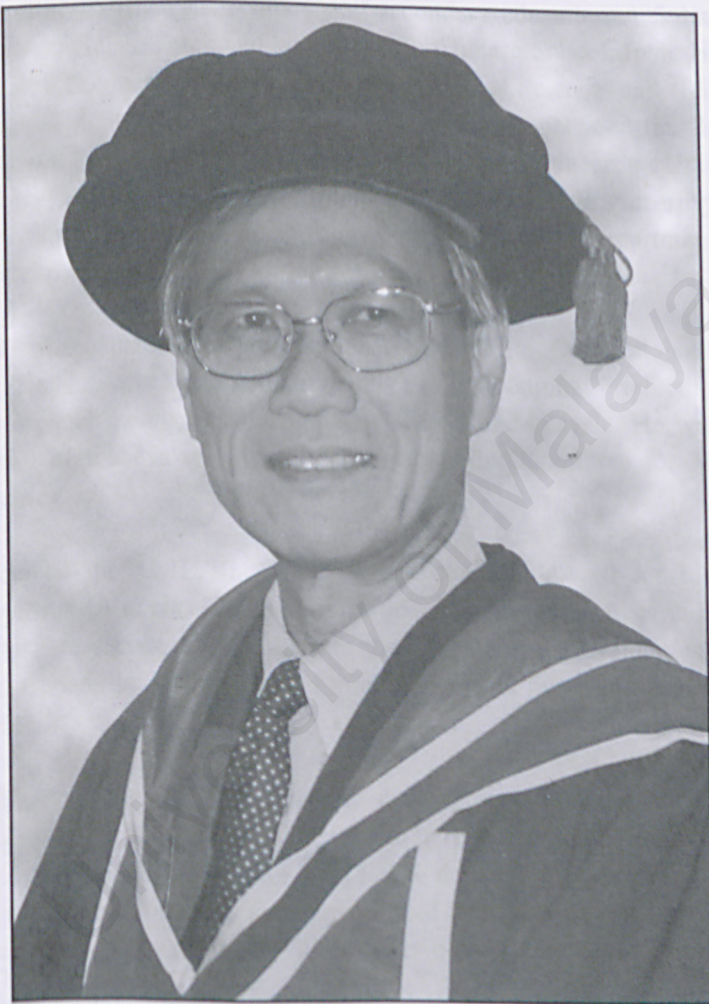
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Professor Dato' Ir Dr. Goh Sing Yau

Curriculum Vitae - Professor Dato' Goh Sing Yau

Dr Goh Sing Yau had his primary and secondary education at Sultan Yussuf School, Batu Gajah, Perak and later at Anglo-Chinese School, Ipoh. He studied Mechanical Engineering at Imperial College of Science and Technology, London University from 1963 until 1971 where he obtained his Bachelor's, Master's and PhD degrees. He joined the Faculty of Engineering, University of Malaya in 1971 and became the Professor of Mechanical Engineering in 1981. He is currently a professor in the Biomedical Engineering Department, Faculty of Engineering.

Dr Goh was a member of the National Council for Occupational Safety & Health. He has served as a council member of the National Productivity Centre and as a panel member of the Industrial Court of Malaysia. He was also the Chairman of the Malaysian Industries Standards Committee for Mechanical Engineering.

He received the 1991 Tun Abdul Razak National Award for his work in developing a PVC plastic hand pump for use in the rural areas in developing countries. He served as consultant to the International Development Research Centre, Canada in developing and monitoring hand pump projects in 11 other countries.

His other research work include the development of a cyclone furnace for burning saw dust waste, an iodinator for introducing iodine into the drinking water in rural areas where there is an iodine deficiency, external fixators for the treatment of tibial fractures and correction of fixed flexion deformity of fingers. His current interest is in direct brain-computer communication and neuroprosthesis.

In 1998, he was conferred the Dato' Paduka Mahkota Perak (DPMP) by Sultan Azlan Shah for his contributions to national development.

In 2004, he was elected to be a Fellow of the Academy of Sciences Malaysia.

Abstract

The human nervous system consists of neuronal circuits that control different types of motor actions. For goal-directed complex coordinated activities, the control circuits require the involvement of the motor control systems found in the motor sensory cortex of the forebrain. Changes in electroencephalogram (EEG) signals registered by electrodes placed on the scalp in the motor sensory cortex areas as a result of actual or imagined movements of parts of the body may be used to control a device, e.g. computer, wheelchair or a neuroprosthesis. As an example of what is involved in developing a Brain Computer Interface (BCI) system, I will describe research work carried out at the Biomedical Engineering Department, University of Malaya to develop an EEG based BCI system for the control of a neuroprosthetic hand. The BCI system consists of EEG electrodes, a BCI box, a computer and a prosthetic finger. Brain EEG signals are acquired through four electrodes placed on the scalp of a subject. The BCI box contains an EEG amplifier and filter, an analog to digital converter (ADC), a universal communication (USB) port and a Fuzzy Logic controller. In the BCI box, the signals from the EEG electrodes are amplified and filtered to remove the unwanted bands of frequencies. The filtered signals are fed into separate ADCs to be digitized. The digitized data are sent via the USB port to the computer where the data are processed and classified. The classification results are sent back through the USB to the Fuzzy Logic controller to drive the prosthetic finger. The BCI box communicates with the computer through a USB communication port. This is selected so that the BCI system can be designed to be independent of the processing unit - the computer. As and when more compact and more powerful portable computers become available, they can be used as the processing unit of the BCI as long as they possess a USB port. The desired manipulative movements of a hand may be reduced to a minimal set of four movements - the pulp-to-pulp pinch, the tripod pinch, the key pinch and the whole hand grasp. A BCI graphic user interface is designed to enable the subject to select each of the four movements by actual or imagined right and left hand movements. The asynchronous BCI neuroprosthetic system was tested on one subject. Video recordings of the experiments show that the subject was able to select the hand movements successfully and activate the appropriate movement of the prosthetic finger.

Direct Brain-Computer Communication and its Application for Neuroprosthesis

1. Introduction

The human nervous system consists of neuronal circuits that control different types of motor actions. For low-level motor actions like the patellar reflex, the sensory neuron - motor neuron - muscle circuit is complete in the spinal cord motor system. For goal-directed complex coordinated activities, the control circuits require the involvement of the motor control systems found in the motor cortex of the forebrain. Through a combination of observation of patients with head wounds and stimulation studies on the motor cortex regions of animals, a cross section of the motor cortex can be drawn to show the positions of neurons that control motor actions of different parts of the body. An example of a cross section of the motor cortex is shown in figures 1.

Biochemical processes inside neurons in the brain produce action potentials that are transmitted along axons. The axons enter the spinal cord and subsequently to the intended muscles for action. The brain action potentials that can be measured may be "evoked" or "spontaneous". Evoked potentials are event related and are produced by an external stimulus. Examples of evoked potentials are visual evoked potentials or P300 evoked potentials. On the other hand, the brain can voluntarily produce spontaneous potentials. Examples of spontaneous potentials are slow cortical potentials, oscillations and cortical neuronal action potentials.

Electrodes that are used to obtain brain signals may be invasive or non-invasive. Non-invasive electrodes are normally placed on the scalp and

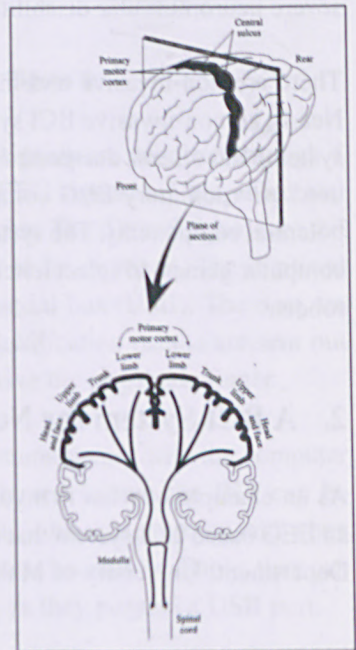


Figure 1

the signals are in the form of electroencephalogram (EEG) signals. Electrodes may be implanted on or in the brain by neurosurgery. Such electrodes may be used to obtain EEG or electrocorticogram (ECoG) signals. Implanted electrodes give better signals but the risk of neurosurgery has prevented more wide scale adoption.

Changes in EEG signals registered by electrodes placed on the scalp as a result of actual or imagine movements of parts of the body may be used to produce a control signal. Pfurtscheller et al (1998) showed that there are Event Related cortical Desynchronization (ERD) and Event Related Synchronization (ERS) of EEG signals obtained from electrodes placed at specific locations on the scalp as a result of actual and imagined hand and foot movements. This may be used in the development of a Brain-Computer Interface (BCI) that can be used to control a device, e.g. computer, wheelchair or a neuroprosthesis that does not depend on the brain's normal output pathways of peripheral nerves and muscles. The BCI system will provide an alternative means of communication to patients with severe neuromuscular disabilities, severe cerebral palsy and paralysis.

There are non-invasive and invasive Brain-Computer Interface (BCI) systems. Nearly all non-invasive BCI systems operate in a synchronous mode. Only a few systems have been designed for asynchronous control. The input brain signals used are oscillatory EEG components, slow cortical potential shifts, or evoked potential components. The systems are used to control cursor movements, to play computer games, to select letters or icons, to operate neuroprostheses and mobile robots.

2. A BCI System for Neuroprosthesis

As an example of what is involved in developing a BCI system, I will describe an EEG based BCI system that is being developed at the Biomedical Engineering Department, University of Malaya for the control of a neuroprosthetic hand.

The system is as shown in Figure 2 and consists of the following elements:

- **A BCI box containing**
An EEG amplifier and filter
An ADC
USB communication port
A Fuzzy Logic Controller
- **A computer containing**
A main program
Signal processing software
- **Electrodes on the scalp**
- **A prosthetic finger**

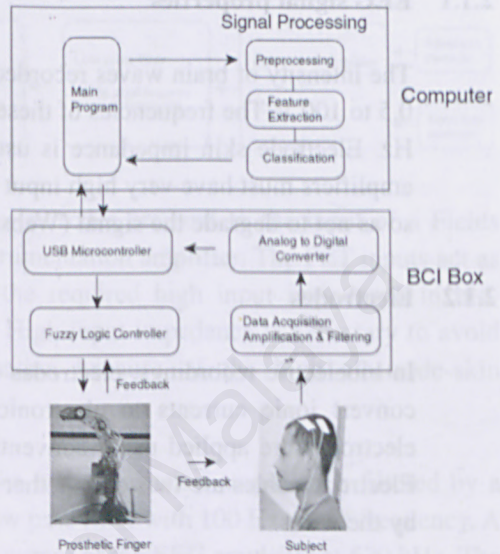


Figure 2

The system is as shown in figure 2. Brain EEG signals are acquired through 4 electrodes placed on the scalp of a subject. The EEG signals are amplified and filtered to remove the unwanted bands of frequencies. The filtered signals are fed into separate analog-to-digital converters (ADC) to be digitized. The digitized data are sent to a computer through a universal serial bus (USB). The data are processed and classified in the computer. The classification results are sent out through the USB to the Fuzzy Logic control to drive the prosthetic finger.

The BCI system is designed so that the BCI box communicates with the computer through a USB communication port. This is selected so that the BCI can be designed to be independent of the processing unit - the computer. As and when more compact and more powerful portable computers become available, they can be used as the processing unit of the BCI as long as they possess a USB port.

2.1 Data Acquisition, Amplification & Filtering

2.1.1 EEG signal properties

The intensity of brain waves recorded using scalp electrodes range from 0.5 to 100 V. The frequencies of these brain waves range from 0.5 to 100 Hz. Electrode skin impedance is usually between 1 k to 10 k . EEG amplifiers must have very high input impedances, typically above 10 M, so as not to degrade the signal (Webster, 1998).

2.1.2 Electrodes

In bioelectric recordings, electrodes are used as signal transducers that convert ionic currents to electronic currents (Webster, 1998). Scalp electrodes are applied using conventional abrasion and conductive gel. Electrode cables are twisted together to minimize magnetic field pickup by the wires.

The electrode montage shown in Figure 3 is used. Two bipolar EEG channels are recorded with gold electrodes placed over the sensorimotor representation areas of the scalp. Channel 1 is derived from an electrode placed at 2.5 cm posterior and 2.5 cm anterior to the C3 respectively whereas Channel 2 is derived from an electrode placed at 2.5 cm posterior and 2.5 cm anterior to the C4. The ground electrode is placed at the mastoid behind the ears to reduce interference.

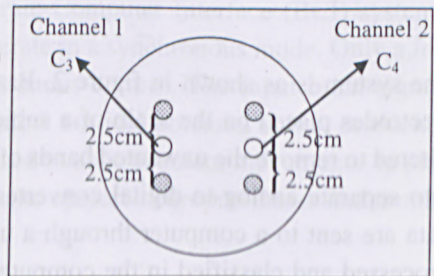
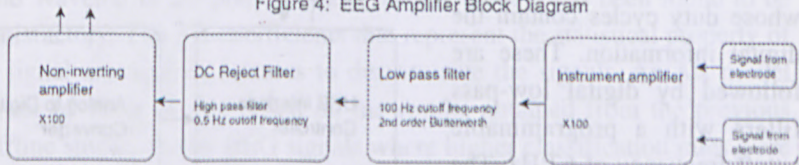


Figure 3: The electrode montage

2.1.3 Circuit Description

Figure 4: EEG Amplifier Block Diagram



The EEG signals from the electrodes are sent to the input of a Fields Effect Transistor (FET) instrumentation amplifier. The FET inputs act as preamplifiers and provide the required high input impedance in bio-potential amplifiers design. High input impedance is necessary to avoid bio-potential signal attenuation because of the high electrode-skin impedance.

The differential output of the instrumentation amplifier is filtered by a second order Butterworth low pass filter with 100 Hz cutoff frequency. A 16-bit ADC will sample the output of the EEG amplifier at 570 kHz. The low pass filter provides adequate attenuation to prevent fold back of high frequency components into the band of interest (0.5Hz to 100Hz) (Baker, 1999).

The filtered signal is sent through a DC reject filter consisting of a simple R-C filter with a cutoff frequency of 0.5 Hz. A DC reject filter is needed to prevent saturation of the amplifier due to electrode-offset voltages. Electrode offset voltages are dc voltages produced by the difference in electrode potentials developed across the electrode-conductive paste interface (Cromwell 1980). The signal is amplified 100 times again with a non-inverting amplifier.

2.2 Analog to Digital Converter & USB Port

The analog to digital (AD) section consists of 4 separate 22-bit sigma-delta ADC channels in a chip and a micro-controller to control the timing of the ADCs. Each of the analog input signals to the ADCs is continuously sampled at 570 kHz. Sigma-delta converters offer high resolution at low cost. Four sigma-delta

modulators convert the sampled signals into digital pulse trains whose duty cycles contain the digital information. These are followed by digital low-pass filters with a programmable cutoff frequency of 67 Hz. The low-pass filters will process the output of the modulators and update the data output register at a rate of 256Hz.

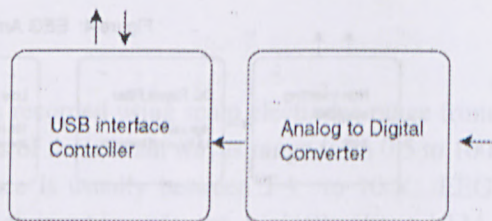


Figure 5: ADC & USB Block Diagram

The USB Receiver consists of a USB micro-controller, an eeprom to store the program and a 2 kByte temporary buffer to store the data. The USB micro-controller packs the intelligence required by a USB peripheral interface into a compact, integrated circuit. An integrated USB transceiver connects to the USB bus. A Serial Interface Engine (SIE) decodes and encodes the serial data and performs error correction, bit stuffing, and other signaling-level details required by USB.

During on-line operation, the controlling program at the host computer will request for 256 samples from each of the 2 channels. Since the sampling rate is 256 Hz, the data transfer will be completed in 1 second. After signal processing and classification of the data, the results of the classification will be sent through the USB to the Fuzzy Logic controller to drive the selected movement of a prosthetic hand. To ensure uninterrupted real time processing, signal processing and classification in the computer must be completed in less than 1 second.

2.3 Signal Processing & Classification

2.3.1 Signal Preprocessing and Features Extraction Algorithm

The signals acquired are digitally filtered using an elliptic 5-40 Hz bandpass filter to increase the signal to noise ratio. Next, the signals are processed to extract useful features. Many different methods have been

used for feature extraction. Examples are Band Power method using ERD and ERS, Autoregressive Parameter, Adaptive Autoregressive Parameter and Wavelet. In the present study, the AR method has been found to be satisfactory. The AR coefficients that represent the statistical property of a signal are used as features to discriminate the signals. An AR model order of 15 is chosen based on the results obtained from the previous offline studies on the EEG signals where higher classification rates were achieved using this model order.

2.3.2 Classification Algorithm

Again there are a number of options in selecting the classification method. Examples are Threshold using ERD & ERS features, Linear Discriminant Analysis (LDA), Artificial Neural Networks and Support Vector Machines. A linear classifier is generally simpler and more robust than a nonlinear classifier. Fisher's Linear Discriminant Analysis is used in this study because LDA requires smaller training samples. This becomes important during online classification. Moreover, it does not assume that the populations are from a multivariate normal distribution. However, the LDA does assume that the populations have a common covariance matrix. The LDA coefficients can be obtained by maximizing the variance between populations.

2.4 Fuzzy Logic Controller for Prosthetic Finger

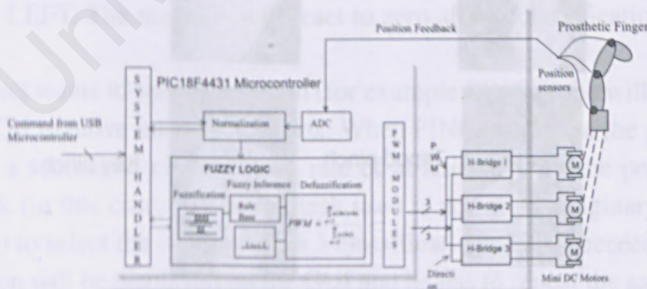


Figure 6: FUZZY LOGIC CONTROLLER FOR PROSTHETIC FINGER

A fuzzy logic controller as shown in figure 6 is developed to control the motion of a prosthetic finger. Each finger has three degrees of freedom and each segment is actuated by a separate dc motor. An H-bridge switch provides speed and bi-directional control to each motor. The control is accomplished by adjusting the Pulse Width Modulation (PWM) duty cycle and a directional signal to the H-bridge. Sugeno Defuzzification technique is used to provide the PWM duty cycle value and the direction of the DC motor. The membership functions are tuned until a good respond is achieved.

3. Implementation of BCI for Neuroprosthesis

3.1 Design of the Graphic User Interface (GUI)

The desired manipulative movements of a prosthetic hand may be reduced to a minimal set of 4 movements as shown in figure 7.

Figure 7: Desired hand movements



Grip



Pulp to Pulp pinch



Tripod pinch



Key pinch

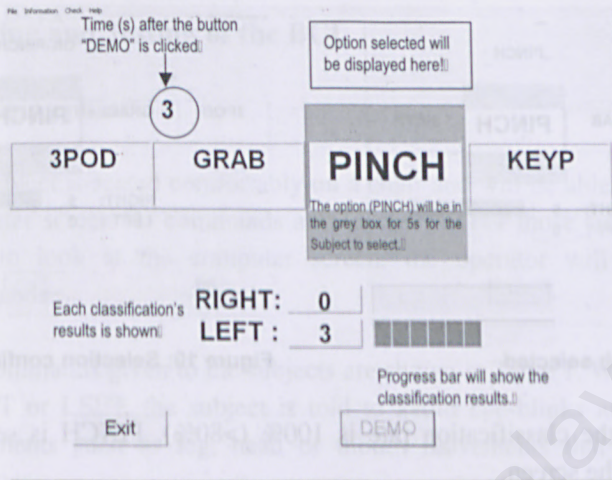


Figure 8: BCI Graphic User Interface

By actual or imagined right or left hand movements, a subject will attempt to select the options from a GUI as shown in figure 8 and operate the 4 desired movements of the prosthetic hand. The 4 options are 3POD (Tripod pinch), GRAB (Grab), PINCH (Pulp-to-Pulp pinch) and KEYP (Key pinch). The options will shift to the next selection box on the right after every 5 classifications. The EEG signals will be processed and classified for every 256 samples. The classification result is shown in the form of numbers and a progress bar. The number next to either Right or Left will increase if the signal is classified as RIGHT or LEFT. The numbers will reset to zero after 5 classifications.

If the subject wants to select an option (for example PINCH), he will wait for the word PINCH to move into the grey box. When PINCH is inside the grey box, he has to get a successful classification rate of at least 80% of the predetermined mental task (in this case, the mental task used is actual or imaginary right hand movement) to select the option within 5 classifications. If he succeeds, the name of the option will be displayed on the GUI and he has to repeat the same or better success rate for the next 5 classifications to confirm his selection. On confirmation of his selection, a control signal is sent to the Fuzzy Logic controller to move the prosthetic hand (Figure 9 and 10). Otherwise, the selection will be canceled.

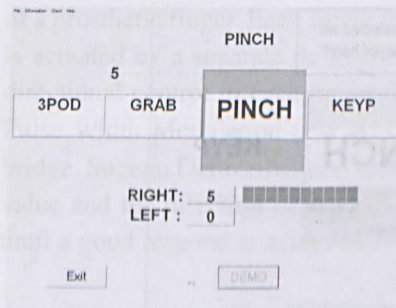


Figure 9: Pinch selected

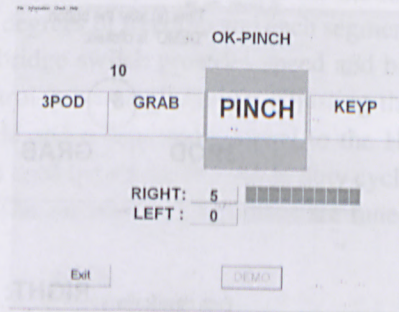


Figure 10: Selection confirmed

In Figure 9, the classification rate is 100% ($>80\%$). PINCH is selected and displayed on the screen.

In Figure 10, the classification rate is 100% ($>80\%$). The selection PINCH is confirmed and displayed on the screen. A control signal is sent to the Fuzzy Logic controller to move the prosthetic hand.

After the action is performed, the computer will wait for the subject to reset the prosthetic hand to its original position. The GUI changes to that as shown in Figure 11. Again, the subject has to achieve classification rate of at least 80% to select RESET within 5 classifications and confirm the selection in the next 5 classifications to reset the prosthetic hand. After the reset, the GUI returns to that as shown in Figure 8.

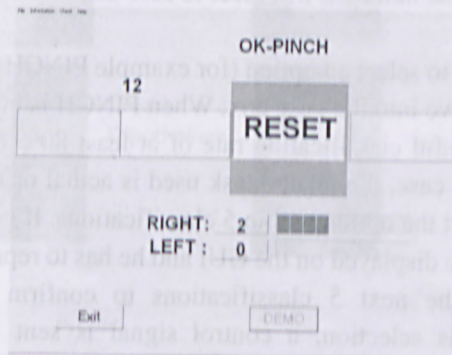


Figure 11. The computer waits for the subject to select the RESET.

3.2 Training and Testing of the BCI

I) Training phase

The subject is seated comfortably on a chair and will be able to look at the computer screen for commands and feedbacks. For those subjects who do wish to look at the computer screen, the operator will provide oral commands.

The commands given to the subjects are shown in Table 1. When executing RIGHT or LEFT, the subject is told to avoid eye-blinks and other body movements such as leg, head or mouth movements that will generate artifacts.

Table 1: Commands given to the subjects.

Instruction	Subject's Action
RIGHT/LEFT	Concentrate and move the right/left hand for T_I s
REST	Stop moving the hand and stay relax (Tr s)

Before the training session, the operator will set the number of training trials (N), duration of each trial (T_I) and the resting interval between 2 trials ($Tr=10$ s). N and T_I are subject-dependent. Some subjects prefer to have a longer T_I because they need more time to concentrate. Some subjects tend to blink frequently and prefer to have a shorter T_I to prevent their eyes from blinking when they are moving their hands. However, T_I should not be less than 5 seconds and the $N \times T_I$ should be more than 240 so that enough training samples are available to train the LDA.

The sequence of the type of actual movements to perform (RIGHT or LEFT) is generated randomly by the computer. For each trial, the signals from both EEG-channels are digitally filtered and the AR coefficients are computed every second with a window size of 256 observations. No overlapping windows are used in processing the data. At the end of the session, $N \times T_I$

training samples are obtained they are used to train the LDA classifier. The subject will rest for a few minutes after the first recording session.

After the LDA is set up from the training samples of the two classes (RIGHT and LEFT), it will be tested with some resting samples (AR coefficients obtained from the EEG signals during resting state). The classifier is likely to be biased to one class. If it is biased to class 1 when the subject is not performing any mental task (REST), then the subject will use the other class (class 2) to make a selection. For the current subject, the classifier is biased to the LEFT when he is not performing actual or imaginary right or left hand movements. In this case, it is possible to set up an asynchronous EEG-based BCI control system where the subject performs imaginary or actual right hand movements to select an option on the GUI.

II) Testing phase

For every 256 observations, the signals are processed and classified by the LDA set up in the first recording session. The subject will look at the screen to select one of the four options available by using the predetermined mental task. The progress of the results of the classification will be displayed on progress bars and numbers beside them.

4. Results and Discussions

The above asynchronous BCI neuroprosthetic system was tested on one subject that has a good record of success in earlier EEG classification tests. Recorded videos of the present BCI experiments carried out on this subject show that he was able to control the prosthetic finger successfully.

Concluding remarks

Other research groups are developing various BCI systems with varying degrees of success. These systems can be used to control cursor movements, to play computer games, to select letters or icons, to operate neuroprostheses and mobile robots.

Further research effort is required to develop better signal processing and classification techniques that can differentiate complex mental tasks.

There is always a need for better brain signals. Implanting electrodes in the brain is a possible solution. With greater experience, the surgical procedures for implanting electrodes in the brain may become simpler and safer.

There are also difficulties in getting consistent brain signals for specific mental tasks because the state of the mind of a subject changes depending on many factors. There is a need to look into what type of mental training will improve the capability of the subject to control his/her brain signals in a way that can be used in a BCI system. Just as we need to learn how to drive a car, we will probably need to be trained to operate a BCI system efficiently.

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